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An Evaluation of the Navy Atmospheric Boundary Layer Model

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ABSTRACT

The results from a test performed to validate the Navy Atmospheric Boundary Layer (NABL) model are presented. Average statistics indicate that NABL forecast temperature profiles compare favorably with those from a 40 km horizontal resolution version of the Navy Operational Regional Atmospheric Prediction System (NORAPS), but that negative (dry) moisture biases are more severe in the NABL model. Test results indicate that the NABL model is superior to NORAPS for short-range forecasting of elevated trapping layers; however, NABL's ability in surface ducting assessment was found to be limited. It is recommended that the NABL model be upgraded to operational status so that its use in refractivity forecasting and in applications programs which require high resolution boundary layer information can be exploited.

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AN EVALUATION OF THE NAVY ATMOSPHERIC BOUNDARY LAYER MODEL

1. INTRODUCTION

In response to the Navy's critical needs for short-range forecasts in the marine boundary layer, the Navy Atmospheric Boundary Layer (NABL) model has been developed. This model has successfully transitioned from exploratory to advanced development and undergone extensive testing in both research and operational environments. In order to transition the NABL model to operational implementation at FNOC (Fleet Numerical Oceanography Center), a validation test report is required. This NOARL Technical Note presents the results from a test performed to validate the NABL model.

The verification of the NABL model is by direct comparison with radiosondes. Statistical differences between NABL model forecast ambient and dewpoint temperatures and radiosondes are calculated. An assessment of the NABL model's ability to forecast refractive structure is established, based on comparisons of model and radiosonde refractivity profiles. In particular, a determination is made as to how well the NABL model is able to assess and forecast the most important anomalous propagation phenomenon to impact naval operations - ducting. In order to assess the degree of skill and usefulness of the NABL model, direct comparisons are made among NABL model forecasts and analogous forecasts from the Navy Operational Global Atmospheric Prediction System (NOGAPS) and a specially implemented version of the Navy Operational Regional Atmospheric Prediction System (NORAPS).

2. NABL MODEL DESCRIPTION

The NABL model is a one-dimensional numerical model designed to make high resolution, short-range (up to 36 hr) predictions in the atmospheric boundary layer. Its main

attributes are sophisticated boundary layer physics, moist thermodynamics and a very high vertical resolution. The model contains prognostic equations for the mean variables - the wind components, liquid water potential temperature and total moisture. Prognostic equations for turbulent kinetic energy, temperature and moisture variances, and their covariances, are given by a second order closure turbulence parameterization. The model's moist thermodynamics calculations include liquid water content and fractional cloudiness; precipitation is calculated based upon an assumed cloud droplet distribution function. A detailed radiation scheme computes fluxes of long and shortwave radiation and heating/cooling rates. The NABL model grid contains 40 points within 4.5 km of the surface (i.e., below ~580 mb), with spacing compacted toward the surface such that 6 points lie within the first 100 m. Vertical resolution ranges from 5 m at the surface to 150 m above 1.5 km. Further details of NABL model physics are given by Burk (1989) and Burk and Thompson (1989).

A unique feature of the NABL model is its coupling to the Navy's operational large-scale models - the NOGAPS and the NORAPS (See Appendix A for descriptions of these models). Operationally, the NABL model is initialized with a vertical profile and surface information from a "host" large-scale model (either NOGAPS or NORAPS). In general, NABL initial gridpoint data are obtained by interpolation from the large-scale model sigma surfaces; however, for those NABL gridpoints below the large-scale model's lowest computational level, initial NABL temperature and humidity values are set equal to those at the lowest surface. If necessary, NABL initial profiles are modified to eliminate superadiabatic or supersaturated layers. During execution, previously saved adiabatic tendencies, at hourly forecast intervals from the host model, are used to represent horizontal and vertical processes not modeled by NABL. For this study, the initial profiles and surface information, as well as the tendencies, from the host NOGAPS (or NORAPS) model are those at the nearest NOGAPS (or NORAPS) gridpoint to the specified

NABL forecast location. In general, the NABL model is quite sensitive to the forecast location type (land or water), which is uniquely specified by the model's ground wetness parameter for that location. For land points, the degree of diurnal variation within the boundary layer is very pronounced, whereas, for water points, it is much less so.

3.   VERIFICATION

3.1   Data

As verification for NABL model forecasts, routine radiosondes from five island sites - Sable Is., CAN (YSA); Cape Hatteras, NC (HAT); Bermuda, U.K. (XKF); Nassau, Bahamas, U.K. (YNN); and Key West,FL (EYW) - and one land station (Greensboro, NC (GSO)) were utilized (Figure 1). With the exception of XKF, all island station elevations (i.e., radiosonde launch heights) were within a few meters of sea level (see Table 1). All sites (except YNN) launch sondes twice daily (00Z and 12Z); YNN has only a 12Z launch schedule. Over the three week period of study (11 April - 01 May 1991), radiosonde availability (from FNOC data records) was near 90% at all sites except YNN, where only 75% of scheduled sondes were available. For comparison with NABL forecast profiles, only lower tropospheric sounding data (surface to ~600 mb) were required. Radiosonde data included both standard and significant levels; each radiosonde was gross error checked to ensure some degree of accuracy and consistency.

Two groups of NABL model forecasts were compared to soundings; one, NABL forecasts coupled to NOGAPS (hereafter designated NABL(NG)) and two, those coupled to NORAPS (NABL(NR)). In both cases, NABL model profiles were loosely co-located with the selected radiosonde sites; that is, the model-derived profile for a location is given by the model profile at the nearest NOGAPS (or NORAPS) gridpoint. In this study, for any particular model run, two
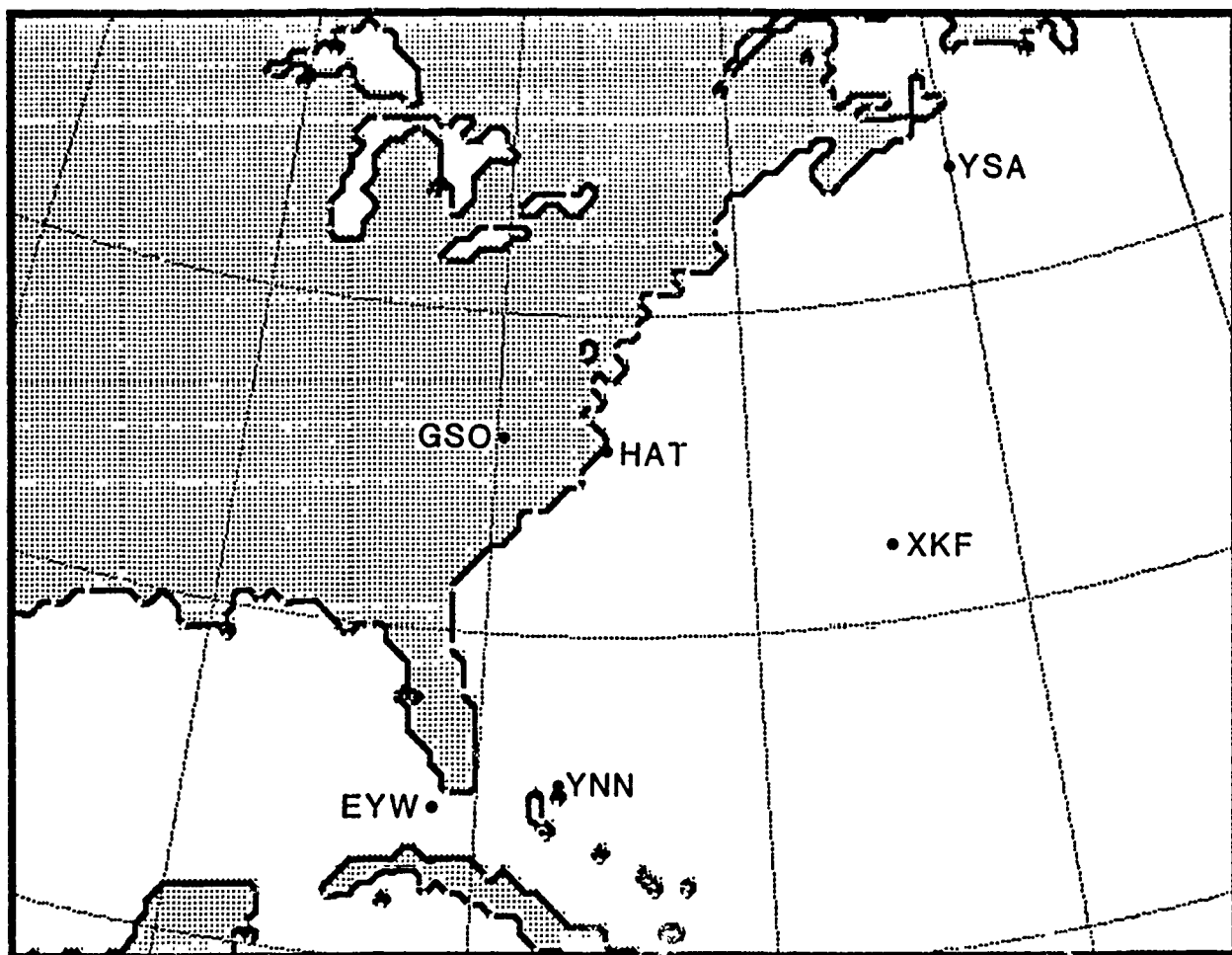
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Figure 1. NORAPS forecast domain and radiosonde locations used in study.

Table 1. Model terrain and radiosonde station heights (in meters) at selected stations: YSA (Sable Is., CAN); HAT, HTL (Cape Hatteras, NC); GSO (Greensboro, NC); XKF (Bermuda, U.K.); YNN (Nassau, Bahamas, U.K.); and EYW (Key West, FL). HAT (HTL) is considered a NABL model water (land) location. No NABL(NG) height is given for GSO; NOGAPS data were not used at this location.

STATION	RADIOSONDE	NABL(NR)	NABL(NG)
YSA	4	0	4
HAT	2	0	1
HTL	2	0	97
GSO	277	233	-
XKF	27	0	-1
YNN	2	0	4
EYW	2	0	4

distinct NABL profiles were available at Cape Hatteras, NC - one considered to be at a water point (HAT), the other over land (HTL). All other NABL forecasts, with the exception of GSO (a land point), were considered to be at water points. Inspection of Table 1 indicates that surface terrain heights slightly exceed zero at several NABL(NG) ocean locations. In general, vertical offsets between radiosondes and corresponding model profiles are not large; offsets > 20 m only occur at XKF, HTL (for NABL(NG)) and GSO. NABL forecasts were made at both 00Z and 12Z start times, with forecasts at tau = 0, 12 and 24. (Note: Tau refers to the model forecast period in hours; tau = 0 is an initial (analysis) field.)

For statistical comparisons with NABL model profiles, NORAPS model-derived profiles (at tau = 12 and 24) were extracted for all study locations. Additionally, these NORAPS profiles (and corresponding NOGAPS profiles at tau = 0 and 12) were used for comparisons of large-scale and NABL model capabilities for refractivity assessment and forecasting. The NOGAPS model-derived profiles used in this study were based on data from the six lowest model

computational levels (i.e., below ~2.3 km when the surface pressure is 1 atm). NOGAPS (NORAPS) terrain heights correspond to NABL(NG) (NABL(NR)) station values given in Table 1.

3.2 Techniques

This validation of the NABL model is based on two main criteria; one, model error statistics and two, capabilities for assessment/forecasting of refractivity structure, in particular, the occurrence of ducting. Additionally, a visual, qualitative evaluation is made of NABL forecast quality in regards to surface layer features. The two statistics utilized in this validation are the bias and the root-mean-square (RMS) difference, and are computed for the temperature and dewpoint temperature. To calculate these statistics, model temperature and dewpoint temperature data are interpolated, assuming a linear variation with the log of the pressure, to all reporting levels (standard and significant) of the corresponding radiosonde which are below the NABL model's highest forecast level (4.5 km or ~580 mb). The temperature and dewpoint temperature differences between the model and radiosonde at all applicable levels are used collectively to compute integral approximations of the bias and RMS difference. Unlike point-by-point approximations (which equally weigh all data in averaging), integral approximations of error statistics assign proportionally more (less) weight in averaging to widely (closely) spaced data within the sounding. Given estimates of bias and RMS difference between each radiosonde and the corresponding model profile, average temperature and dewpoint temperature error statistics can be readily computed for any one station or group of stations (e.g., those at water points), or for a particular forecast tau or verification time. In this study, average error statistics are compared among NABL(NG), NABL(NR) and NORAPS forecasts.

Given conventional radiosonde or model profile data, an assessment of ducting can conveniently be made in terms of the modified refractivity M, which is expressed as,

$$M = 77.6p/T + 3.73 \times 10^5 \ e/T^2 + 0.157z \ ,$$

where p is the atmospheric pressure in millibars,

T is the temperature in Kelvin,

e is the vapor pressure in millibars, and

z is the height above the sea surface in meters.

Whenever M decreases with altitude within a layer (dM/dz < 0), a trapping layer is present, and enhanced microwave propagation occurs within the duct below the top of the trapping layer for small incidence angles. A duct can be either surface or elevated; a surface-based duct can result from an elevated trapping layer (ETL) provided that the value of M at the top of the ETL is less than the value of M at the surface.

Radiosonde M-profiles were computed from mandatory and significant sonde levels within the lower troposphere. This required the conversion of dewpoint temperatures at reporting sonde levels to vapor pressures, and the determination of sounding heights at significant levels through application of the hypsometric formula. In general, the vertical resolution of any particular radiosonde-derived M-profile, which is a function of the number of significant levels, is in proportion to the complexity of lower tropospheric meteorological conditions. On the other hand, the vertical resolution of a NABL model M-profile is invariant and that of a NOGAPS or NORAPS profile is, for all practical purposes, also fixed. In this study, differences in vertical resolution between radiosonde and model M-profiles are not resolved; comparisons of ducting occurrence among model forecasts and soundings will be based on actual model and radiosonde resolution.

A cursory examination of all NABL forecasts available for this study indicates a large number with very shallow surface ducts. In general, very shallow surface ducts cannot be resolved by radiosondes and thus, should be eliminated from comparisons. To accomplish this, an analysis criterion was set to eliminate all very shallow NABL surface ducts. This criterion states that a NABL surface duct will be considered to have occurred if a model profile surface-based duct height ≥ 40 m occurs.

In regards to elevated ducting, an elevated trapping layer will be considered to occur for any profile (radiosonde or model-derived) provided that the top of any one ETL is at least 40 m above the surface and no more than 2.3 km above the surface. The upper limit for ETL occurrences essentially applies only to radiosondes, since model (NOGAPS, NORAPS or NABL) ETL occurrences do not generally occur above 1.5 km. The occurrence of multiple ETLs in a profile will be counted as one occurrence. A "correct" model forecast of an ETL is not restricted by any condition which would require the forecast ETL to be located within a certain specified range of the observed ETL.

The verification of any particular model's ability to assess or forecast ducting will be based primarily on two simple contingency table statistics, the prefigurance (P_f) and the postagreement (P_a). Given any particular event (viz., ducting), the prefigurance is the capability of correctly forecasting that event, and is defined as the number of correct (model) forecasts divided by the number of observed (radiosonde) occurrences. Postagreement is the reliability of the forecasts that were issued, and is defined as the number of correct (model) forecasts divided by the number of forecasts issued.

4.   COMPARISON RESULTS

The evaluation of a model's meteorological and refractive structures by direct comparison with soundings (as per this study) is certainly not a fully adequate method. A radiosonde represents only one "snapshot," or realization, from a turbulent medium, providing point measurements which define significant temperature and/or moisture locations in the vertical. On the other hand, a model profile reflects a volume-averaged atmospheric structure, one where sharp gradients are often not well analyzed. Particularly in coastal regions, this fundamental difference can lead to a direct comparison of a maritime radiosonde with a continental co-located model profile. Differences in vertical resolution, and vertical offsets between radiosondes and corresponding model profile also adversely affect direct comparisons.

4.1   Statistics

In this study, the temperature and dewpoint temperature serve as the basic atmospheric parameters for model validation. Unlike the case for temperature, statistical results based on dewpoint temperature are difficult to interpret. This moisture parameter tends to be overly sensitive, especially away from the surface, where large differences in dewpoint temperature only equate to small differences in actual water vapor content.

A comparison of NORAPS, NABL(NR) and NABL(NG) error statistics for temperature, based on all available water point forecasts (i.e., YSA, HAT, XKF, YNN and EYW), is presented in Figure 2. These model statistics are based on a total of 130, 135 and 136 coincidental forecasts, at tau = 0, 12 and 24, respectively. NABL(NR) and NABL(NG) mean RMS differences are seen to increase roughly a degree from the initial (analysis) time to tau = 24. NABL values at tau = 12 and 24 are only a few tenths of a degree greater than values for NORAPS. These slight differences practically disappear when one considers median RMS differences; in particular, median RMS temperature differences among models differ by no more
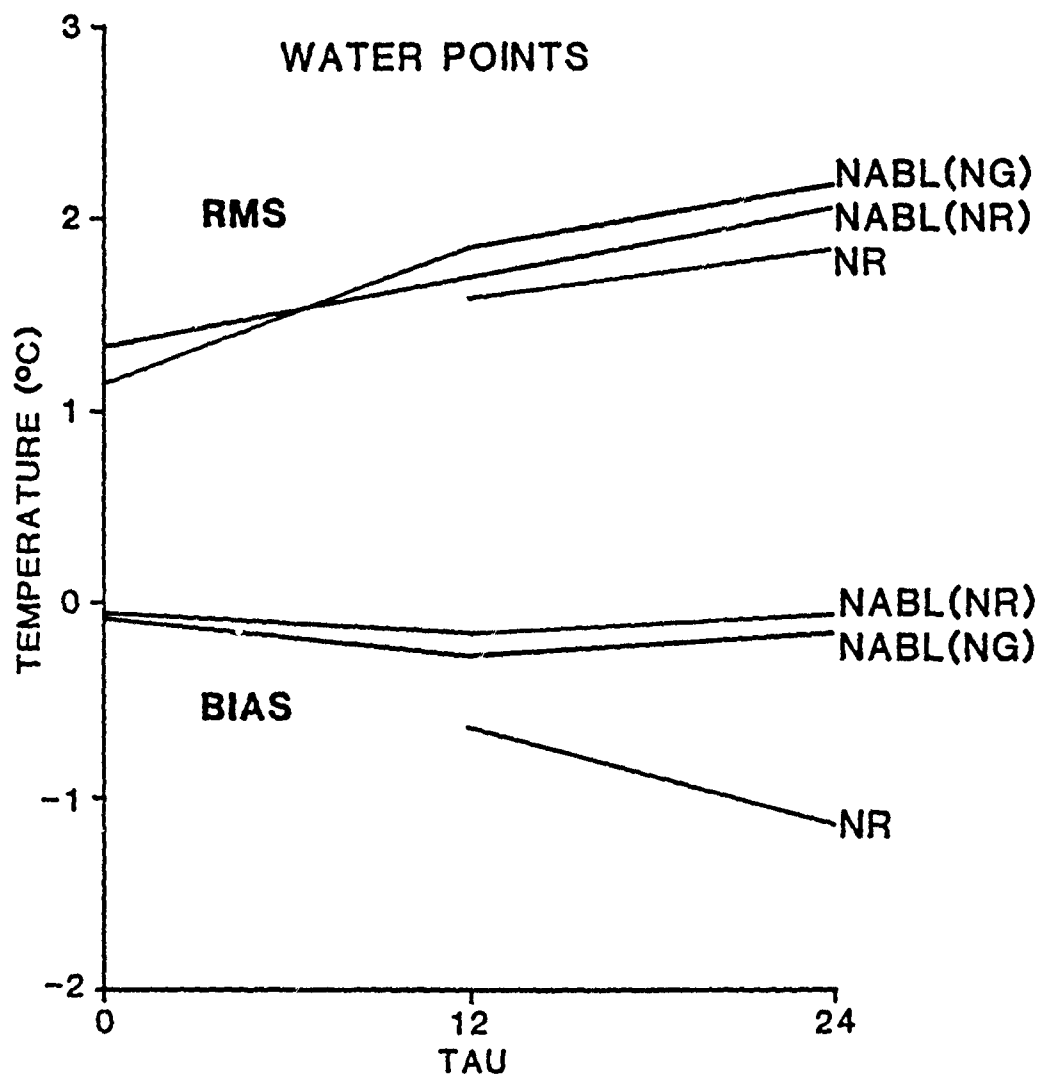
Figure 2. Comparison of NORAPS, NABL(NR) and NABL(NG) mean RMS difference and bias statistics for temperature, derived from all available water point forecasts, at tau = 0, 12 and 24.

than a tenth of a degree at tau = 12 and 24. Mean NABL temperature biases are not significant, and are within a few tenths of a degree of zero over the entire forecast period. On the other hand, the NORAPS model exhibits a markedly cold bias (forecast lower than observed) which increases about a half degree from tau = 12 to tau = 24. A total of almost 90% of NORAPS forecasts at tau = 24 had cold biases. NABL(NR) forecasts did not indicate any decided bias (warm or cold) in terms of frequency; the percentage of NABL(NG) forecasts with a cold bias increased only slightly over the forecast period, from 55% at tau = 0 to 63% at tau = 24.

Figure 3 depicts the NABL and NORAPS mean RMS difference and bias statistics for dewpoint temperature, derived from all available water point forecasts. In general, the RMS differences and biases are quite large, reflecting both the sensitivity of dewpoint temperature as a moisture parameter and the lack of a moisture analysis with either NOGAPS or NORAPS. Mean NABL RMS differences increase roughly 2°C over the forecast period. Differences between NORAPS and the NABL model are not great, and increase from about a half degree at tau = 12 to about one degree at 24 hours. Mean dewpoint temperature biases for the NABL model are slightly negative initially, but increase rapidly over the forecast period. Although difficult to interpret, this marked increase in negative bias for dewpoint temperature suggests that the NABL model's initial moisture distribution tends to dry out over time. The NORAPS negative dewpoint temperature biases, which are less severe than those for NABL, are seen to increase only slightly from tau = 12 to tau = 24. The difference between these NORAPS biases and corresponding NABL biases increases considerably over this forecast time interval. Finally, when median values are considered, both the dewpoint temperature RMS difference and negative bias for NABL(NG), at tau = 12, are actually slightly less than the corresponding values for NORAPS.
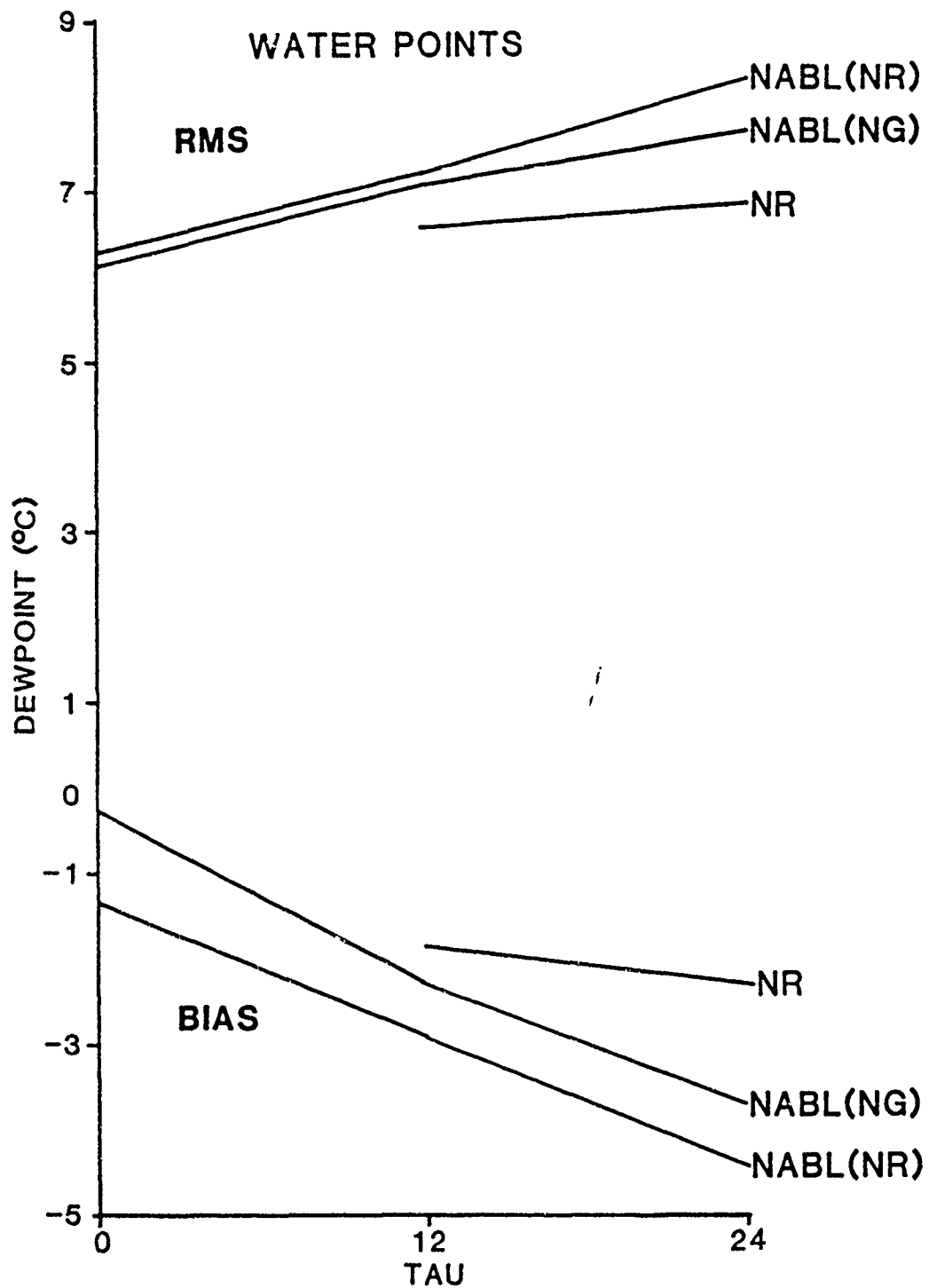
Figure 3. Comparison of NORAPS, NABL(NR) and NABL(NG) mean RMS difference and bias statistics for dewpoint temperature, derived from all available water point forecasts, at tau = 0, 12 and 24.

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A direct comparison of model land and water point forecasts is available only at one site - Cape Hatteras, NC. Table 2 presents NORAPS, NABL(NR) and NABL(NG) mean RMS difference and bias statistics at HAT (water point) and HTL (land point). Statistics given in this table are based on only 30 forecasts for each tau, and thus lack a strong statistical base. At each forecast period, temperature and dewpoint temperature mean RMS differences for all models are larger for land forecasts. The magnitude of these differences between land and water forecasts is most noticeable for NABL(NG), and exceed $1^\circ C$ at tau = 24. Mean temperature biases for NORAPS and NABL also show a common trend throughout the forecast period, that is, more negative for land point forecasts NABL(NG) again presents the greatest difference between land and water forecast about $1.4^\circ C$ at all forecast intervals. With the exception of NORAPS at tau = 12 and NABL(NR) at tau = 0, dewpoint temperature biases are also larger (i.e., more negative) for land forecasts. Differences between NABL(NG) land and water point model statistics could possibly be influenced by differences in model terrain height in addition to different forecast surfaces (land or water). Unlike NABL(NG) water point forecasts, which begin near sea level, NABL(NG) land point forecasts start at almost 100 m above the surface; radiosonde data below this height do not enter into computations of model statistics.

In order to examine temporal differences in model statistics, water point forecasts were divided into two groups at each forecast period - those which verify at 00Z, and those at 12Z. Results from these statistical comparisons revealed no noticeable differences. Excepting the previous comparison of HAT and HTL model error statistics, comparisons between individual stations are not pursued in this study due to the relatively low sample size, which adversely affects the reliability of statistical comparisons.

Table 2. (a) Mean RMS difference and bias statistics for temperature (in °C), derived from NORAPS, NABL(NR) and NABL(NG) water (HAT) and land (HTL) point forecasts at Cape Hatteras, NC, at tau = 0, 12 and 24. (b) Same as (a), except for dewpoint temperature.

(a)	TEMPERATURE						
		RMS			BIAS		
TAU	NR	NABL(NR)	NABL(NG)	NR	NABL(NR)	NABL(NG)	
00		1.34	1.20		.16	- .02	HAT
00		1.49	1.97		-.13	-1.33	HTL
12	1.44	1.52	1.58	- .50	-.29	- .07	HAT
12	1.64	1.67	2.51	- .84	-.53	-1.47	HTL
24	1.72	2.04	2.03	- .99	-.18	.26	HAT
24	1.93	2.15	3.04	-1.30	-.34	-1.14	HTL

(b)	DEWPOINT TEMPERATURE						
		RMS			BIAS		
TAU	NR	NABL(NR)	NABL(NG)	NR	NABL(NR)	NABL(NG)	
00		5.74	4.87		-1.59	.23	HAT
00		5.75	5.73		-1.33	.11	HTL
12	5.89	6.21	5.75	-1.57	-1.79	- .82	HAT
12	5.95	6.45	6.44	-1.33	-2.19	-1.81	HTL
24	5.81	6.62	6.79	- .92	-1.92	-2.24	HAT
24	6.01	7.13	8.12	- .97	-2.98	-3.11	HTL

4.2 Refractivity

Due to model limitations, the surface ducting assessment capabilities of the NOGAPS and NORAPS are, for all practical purposes, nil. Table 3 presents the prefigurance and postagreement statistics for the NABL model for surface ducting assessment. A noticeable feature of these data are the low number of observed as well as forecast surface ducts, most especially at water point sites. Although statistically sound conclusions cannot be drawn from small sample sizes, results in Table 3 do suggest that the usefulness of NABL model forecast information in defining surface

Table 3. (a) Surface ducting prefigurance and postagreement statistics for NABL(NG) and NABL(NR), derived from all available water point forecasts. NABL model subscripts indicate forecast tau. (b) Same as (a), except for all available land point forecasts. NABL(NG) forecasts are only available at HTL. Note that postagreement is undefined for $NABL(NG)_0$.
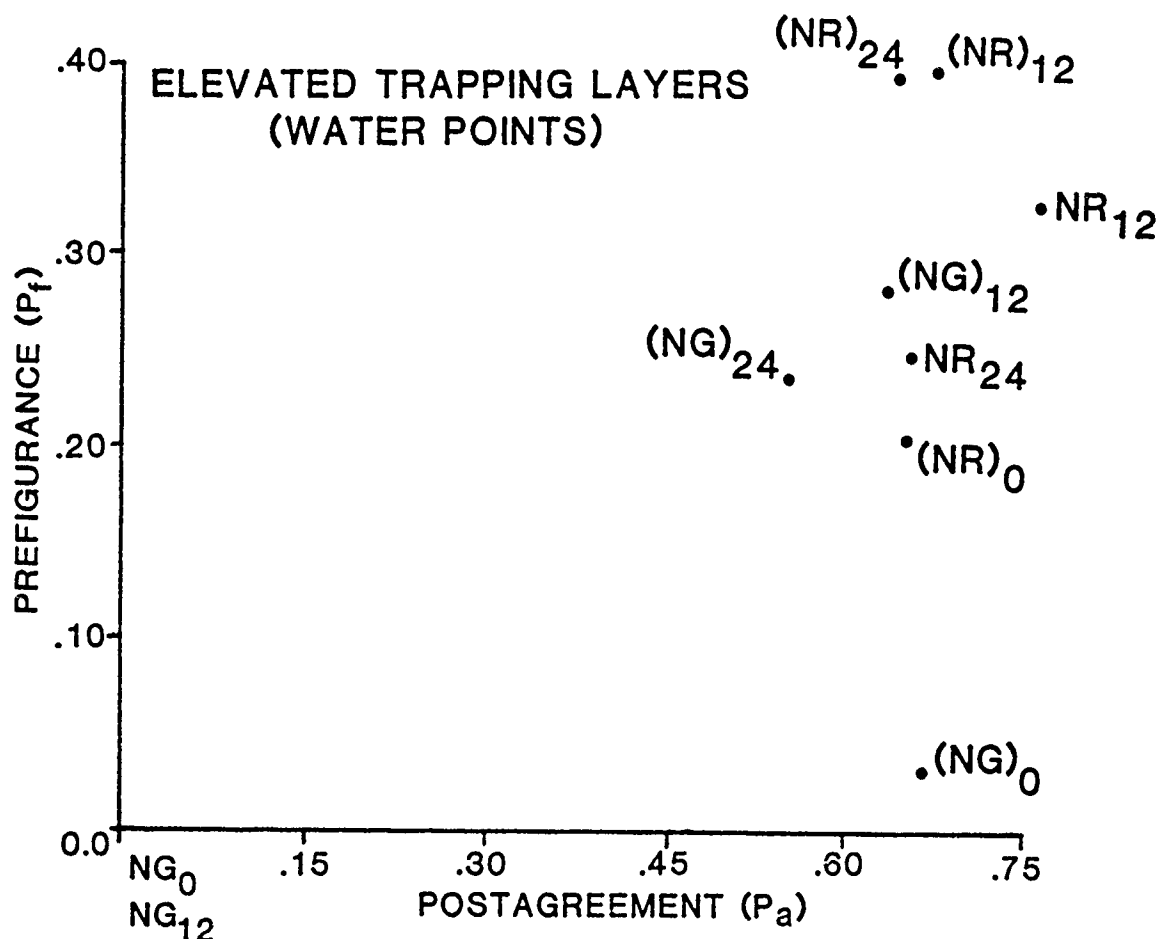
(a) MODEL	NO. DATA	PREFIGURANCE	POSTAGREEMENT
$NABL(NG)_0$	128	0/9 = .000	0/1 = .000
$NABL(NR)_0$	128	1/9 = .111	1/1 = 1.000
$NABL(NG)_{12}$	133	2/10 = .200	2/3 = .667
$NABL(NR)_{12}$	133	0/10 = .000	0/4 = .000
$NABL(NG)_{24}$	134	2/11 = .182	2/7 = .286
$NABL(NR)_{24}$	134	0/11 = .000	0/10 = .000

(b) MODEL	NO. DATA	PREFIGURANCE	POSTAGREEMENT
$NABL(NG)_0$	29	0/7 = .000	0/0 = (UNDF)
$NABL(NR)_0$	59	0/14 = .000	0/1 = .000
$NABL(NG)_{12}$	30	2/7 = .286	2/9 = .222
$NABL(NR)_{12}$	61	3/14 = .214	3/18 = .167
$NABL(NG)_{24}$	30	2/7 = .286	2/11 = .182
$NABL(NR)_{24}$	61	3/14 = .214	3/16 = .188

ducting occurrences is quite limited. This conclusion is the same as that drawn in a previous, more extensive study on forecast model capabilities in ducting assessment (Vogel, 1991).

In that earlier study, Vogel found evidence that NABL 12 and 24 hour land forecasts had markedly higher capabilities and reliabilities at the 00Z verification time than at VT 12Z. A careful examination of available NABL (NG and NR) forecasts at both land locations (HTL and GSO) also shows a similar feature. These temporal differences in NABL 12 and 24 hour land forecasts were likely caused by a bias in the model's surface-energy budget equation for ground temperature. Finally, although data are limited, a direct comparison of land and water point forecasts - at Cape Hatteras - reveals that NABL (NG and NR) 12 and 24 hour surface duct forecasts are more likely over land than water; this finding is in agreement with the previous study by Vogel.

Performance statistics of the NOGAPS, NORAPS and the NABL model for the assessment and/or forecasting of elevated trapping layers, derived from all available water point data, are presented in Figure 4. NOGAPS, based on a limited subset of data at tau = 0 and 12, is found to be completely useless for ETL assessment. On the contrary, NORAPS 12 and 24 hour forecasts show some capability, and quite good forecast reliability. In the previous study by Vogel, no ETL assessment utility was found for NORAPS. Factors which likely contributed to the significant improvement in NORAPS's performance include improved model physics (and computer code), a higher model horizontal resolution (40 km versus 100 km) and the inclusion of a 12 hr incremental update cycle. At tau = 0, NABL(NR) shows considerably better forecast capability than NABL(NG); in addition, NABL(NR)$_0$ had a considerably greater number of reliable forecasts. NABL(NR) 12 and 24 hour forecast capabilities (both near 0.4) are noticeably better, especially at tau = 24, than those for NORAPS. Moreover, although NABL 12 and 24 hour forecast reliabilities are similar to those for NORAPS, the actual number of correct forecasts (and forecasts issued) is somewhat greater for NABL(NR). In general, NABL(NG) 12 and 24 hour forecasts are not good as those for NABL(NR); moreover, while NABL(NG) 12 and 24 hour ETL forecast capabilities are comparable to those for NORAPS, forecast reliabilities appear somewhat less. The better vertical and horizontal resolution of NORAPS compared to NOGAPS is likely the key contributing factor as to why NABL(NR) ETL forecasts are better than those based on NOGAPS information. Finally, although NORAPS and NABL(NG and NR) performance statistics at tau = 12 appear slightly better than those for 24 hour forecasts, these differences are not statistically significant based on the sample size. Interestingly, in the previous study by Vogel, NABL(NR) 24 hour performance statistics were slightly better than those at 12 hr; however, in that case, NABL initial profiles did not benefit from a 12 hr NORAPS update cycle.

Figure 4. Elevated trapping layer prefigurance and postagreement statistics for the NOGAPS, NORAPS and the NABL model, derived from all available water point forecasts. Subscripts indicate forecast tau. Note that postagreement in undefined for NOGAPS at tau = 0 and 12.

The chart shows PREFIGURANCE (P_f) on the vertical axis (0.0 to .40) and POSTAGREEMENT (P_a) on the horizontal axis (0.0 to .75) for ELEVATED TRAPPING LAYERS (WATER POINTS), with data points labeled $(NR)_{24}$, $(NR)_{12}$, NR_{12}, $(NG)_{12}$, $(NG)_{24}$, NR_{24}, $(NR)_0$, $(NG)_0$, NG_0, NG_{12}.

MODEL	NO. DATA	PREFIGURANCE	POSTAGREEMENT
NOGAPS NG_0	68	0/35 = .000	0/0 = (UNDF)
NABL(NG)$_0$	130	2/64 = .031	2/3 = .667
NABL(NR)$_0$	130	13/64 = .203	13/20 = .650
NOGAPS NG_{12}	52	0/30 = .000	0/0 = (UNDF)
NORAPS NR_{12}	135	22/68 = .324	22/29 = .759
NABL(NG)$_{12}$	135	19/68 = .279	19/30 = .633
NABL(NR)$_{12}$	135	27/68 = .397	27/40 = .675
NORAPS NR_{24}	136	17/69 = .246	17/26 = .654
NABL(NG)$_{24}$	136	16/69 = .232	16/29 = .552
NABL(NR)$_{24}$	136	27/69 = .391	27/42 = .643

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For this validation, the capabilities of the NORAPS and the NABL(NG and NR) models to assess relatively deep ($\geq$ 100 m thick) elevated trapping layers were also determined. In general, these results are little changed from those based on all ETL occurrences (Fig. 3). Finally, given the low sample size, a direct comparison of NABL(NG and NR), and NORAPS, land and water point forecasts at Cape Hatteras showed no significant differences in ETL assessment performance.

4.3   Qualitative Evaluation of Forecast ABL

A purely statistical approach to model evaluation can produce misleading conclusions, even when both RMS errors and forecast bias are taken into consideration. For example, a low RMS error or bias statistic does not provide any information concerning features such as mixed layer depth or lapse rate that may be of tactical interest.

A visual, qualitative evaluation was made of the forecasts generated by the NABL model and NORAPS against the verifying raobs. Particular attention was given to forecast quality in the surface layer. "Good" forecast features include a correct depiction of the lapse rate (stable or unstable) in the surface layer. If there is a surface-based inversion, does the model accurately forecast the inversion depth? If the lapse rate in the surface layer is unstable with a mixed layer, is the depth of the well-mixed layer accurate? Does the model forecast a cloud at the top of the mixed layer?

Inspection of selected forecasts from the April 1991 model simulations reveals some of the strengths and weaknesses of the models. NABL with NOGAPS tendencies forecasts the most frequent and deepest mixed layers, but is also more likely to over-predict the mixed layer depth and to predict a mixed layer when the observed near-surface lapse rate is stable. It is possible

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that the relatively coarse vertical resolution of the NOGAPS temperature tendencies when interpolated to the finer NABL model grid produces superadiabatic lapse rates that are removed in the NABL model by vertical mixing in unrealistically deep layers.

The NABL model does somewhat better at forecasting mixed layer structure when the large-scale tendencies are obtained from NORAPS rather than NOGAPS. However, as mentioned in Section 4.1, in both configurations the NABL model does have a dry bias, which can have adverse effects on fog or cloud development. This can be significant, because cloud-top radiational cooling is a major forcing mechanism in the deepening of well-mixed layers. The cause of the dry bias, which may be due to effects of cumulus convection in the large-scale tendency terms, is under investigation.

Excessive moisture in mixed layers is seen in the NORAPS forecasts at the sites selected for the April 1991 evaluation period. Clouds and saturated layers are often too deep in the NORAPS forecasts. In terms of predicting mixed layer structure, the NABL(NR) and NORAPS forecasts are of roughly equal quality. Again, it is the NABL model ability to forecast elevated trapping layers that makes its forecast of value beyond the NORAPS forecast.

4.4   A Few Words About Climatology

Given an assessment of model forecast performance, it is often appropriate to determine if climatology might also provide useful guidance to the forecaster. For example, the NABL model skill at predicting elevated trapping layers, which was discussed in Section 4.2, can be compared to a simple yes/no approach using climatology.

During the verification period of April 1991, the number of elevated trapping layers observed at Key West had an overall occurrence rate of about 0.65 (19 of 30 raobs), which is slightly above the expected climatological rate of 0.55 (Patterson, 1982). If only this one statistic

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was involved in a decision, an elevated trapping layer could be forecast every time with ~65% reliability. The climatology postagreement score would be ~0.65 (19/30) and the climatology prefigurance (skill) score would be 1.0 (19/19). There would be 11 "false alarm" climatology ETL forecasts.

The NABL(NR) model postagreement score for Key West during April 1991 was near 0.7, so it can be stated that the model is at least as reliable in this sense as climatology. However, NABL failed to predict some trapping layers, so the model prefigurance score was less than climatology at this location.

Of course climatology has no utility for forecasting ETL occurrence if values are less than 50%, which is common for many regions and times of year. In addition, the model provides guidance for height of the elevated trapping layer, which is only available at limited locations or on highly smoothed charts from climatology.

5.   CONCLUSIONS

This Technical Note presents the results from a test performed to validate the NABL model, a required step toward operational implementation at FNOC. This validation of the NABL model is by direct comparison with radiosondes and is based on two main criteria; one, error statistics and two, capabilities for the assessment and short-range forecasting of lower tropospheric ducting. In order to assess the degree of skill of the NABL model in predicting meteorological and refractive structure, NABL model forecasts were directly compared with those from a specially implemented, high horizontal resolution (40 km) version of the NORAPS.

Model error statistics are calculated as integral approximations of the bias and RMS difference between model profiles and radiosondes. A comparison of NABL and NORAPS statistics, based on some 135 coincidental model forecasts at 5 island (water point) locations,

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indicates that median RMS temperature differences for these models differ only slightly at either the 12 or 24 hour forecast interval. Mean NABL temperature biases are found to be close to zero at all forecast intervals; on the other hand, the NORAPS model exhibits a pronounced cold bias which increases considerably from tau = 12 to tau = 24. In general, dewpoint temperature RMS difference and bias statistics for the NORAPS and NABL model are quite large; this reflects both the sensitivity of the dewpoint temperature as a moisture indicator and the lack of a moisture analysis with either NOGAPS or NORAPS. Mean dewpoint temperature RMS differences for the NORAPS model are somewhat lower (by ~0.5°C at tau = 12, ~1.0°C at tau = 24) than corresponding values for the NABL model. Both NORAPS and the NABL model indicate negative (i.e., dry) dewpoint temperature biases; not only are the NABL model's 12 and 24 hour negative biases more pronounced, they are also found to increase quite rapidly over the forecast period. In general, a direct comparison of a limited number (30) of land and water point forecasts indicates somewhat larger (more negative) temperature and dewpoint temperature RMS differences (biases) over land than water for both the NORAPS and the NABL model.

With regards to refractivity, evaluation of the NABL model indicates only a limited capability and reliability in the assessment and short-range forecasting of surface ducts. Nonetheless, this minor utility for surface ducting assessment is a modest improvement over the virtually useless capabilities of the NOGAPS and NORAPS. Although data were very limited, an examination of available NABL 12 and 24 hour surface duct forecasts at land points revealed temporal differences in assessment performance, a feature previously found in a similar, more extensive study (Vogel, 1991). Model performance statistics for the forecasting of elevated trapping layers show a decided advantage of NABL(NG) over NOGAPS at tau = 12. While both NORAPS and NABL(NR) 12 and 24 hour ETL forecast reliabilities are very good (near 0.7), NABL(NR) 12 and 24 hour forecast capabilities (both near 0.4) are considerably better than those

NABL(NR) ETL performance statistics were notably higher than those for NABL(NG); here, the better vertical and horizontal resolution of NORAPS compared to NOGAPS is likely the key contributing factor. Finally, the limited data available in this study did not reveal any significant enhancement of ETL forecasting performance when only relatively deep ($\geq$ 100 m thick) elevated trapping layers were considered, nor show any significant differences in NORAPS or NABL ETL performance statistics at land and water locations.

Statistical comparisons of NABL model forecasts of temperature and moisture with those from a high horizontal resolution version of NORAPS do not in themselves indicate a superiority of the boundary layer model. Although temperature profiles compare favorably with those for NORAPS, negative (dry) moisture biases appear more severe in the NABL model. When model forecasts of temperature and moisture are combined to produce refractivity structure, the NABL model shows a noticeable advantage in forecasting performance over NORAPS. The key ingredient for NABL's superiority in refractivity forecasting is likely the model's very high vertical resolution. Although not evaluated here, the NABL model high resolution profiles of temperature and moisture are likely to be of substantial forecasting utility for boundary layer quantities of direct interest besides refractivity. Given the Navy's present critical needs for detailed boundary layer information, it is strongly recommended that the NABL model be put into immediate operational use.

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APPENDIX A - LARGE-SCALE MODELS

NOGAPS

The Navy Operational Global Atmospheric Prediction System (NOGAPS), which is run twice daily (00Z and 12Z) at the FNOC, consists of a multivariate optimum interpolation (MVOI) analysis, a non-linear normal mode initialization scheme, and a triangular 79 wave, 18 level spectral forecast model (Barker et al., 1988; Hogan et al., 1991). The MVOI analysis, which includes a 6 hr update cycle executed 4 times daily, produces a global analysis for the 15 standard pressure levels (along with the 925 mb level) on the 1.5 degree Gaussian grid of the spectral forecast model. The meteorological variables analyzed are the geopotential height and the wind; the virtual temperature is derived by maintaining an approximate hydrostatic balance between the height and wind fields. Since the NOGAPS currently has no moisture analysis, the moisture field from the previous model run becomes the initial moisture field for the next forecast. During the forecast model initialization process, meteorological fields are interpolated, using cubic splines, from the analysis levels to the model grid. The spectral forecast model uses a hybrid sigma vertical coordinate; in such a system, the lowest levels closely follow the model terrain whereas the upper few surfaces are virtually constant-pressure surfaces. As formulated, initial and forecast values of temperature and moisture adjacent to (2 m above) the model surface are derived from data at the lowest model sigma level by assumption of a well-mixed (viz., constant specific humidity) adiabatic surface layer.

NORAPS

The Navy Operational Regional Atmospheric Prediction System (NORAPS) consists of a multivariate optimum interpolation analysis, a non-linear vertical mode initialization, and a 21 level gridpoint forecast model. The NORAPS analysis method is adapted from the NOGAPS

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MVOI scheme, and includes a 12 hr incremental update cycle. Similar to NOGAPS, the regional model does not have a moisture analysis; rather, the 12 hr forecast field from the previous model run serves as the moisture analysis at the next analysis time. During the forecast initialization process, meteorological fields are interpolated, assuming a linear variation with the log of the pressure, from the analysis levels to the forecast model's computational levels. Like NOGAPS, the regional model uses a first order K-theory closure formulation for the planetary boundary layer. The NORAPS version used in this study, which provided short-range forecasts out to 24 hr, was run on a specially implemented 40 km horizontal resolution Lambert conformal grid covering the eastern United States and the western North Atlantic Ocean (Figure 1).

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REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. Agency Use Only *(Leave blank).*	2. Report Date. August 1991	3. Report Type and Dates Covered. Final

4. Title and Subtitle.

An Evaluation of the Navy Atmospheric Boundary Layer Model

6. Author(s).

G.N. Vogel and R.H. Langland

5. Funding Numbers.

Program Element No. O&M,N

Project No. FNOC

Task No. --

Accession No. DN658754

Work Unit No. 6.3-22 (FNOC)

7. Performing Organization Name(s) and Address(es).

Naval Oceanographic and Atmospheric Research Laboratory
Atmospheric Directorate
Monterey, CA 93943-5006

8. Performing Organization Report Number.

NOARL Technical Note 160

9. Sponsoring/Monitoring Agency Name(s) and Address(es).

Fleet Numerical Oceanography Center
Monterey, CA 93943-5005

10. Sponsoring/Monitoring Agency Report Number.

NOARL Technical Note 160

11. Supplementary Notes.

12a. Distribution/Availability Statement.

Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*

The results from a test performed to validate the Navy Atmospheric Boundary Layer (NABL) model are presented. Average statistics indicate that NABL forecast temperature profiles compare favorably with those from a 40 km horizontal resolution version of the Navy Operational Regional Atmospheric Prediction System (NORAPS), but that negative (dry) moisture biases are more severe in the NABL model. Test results indicate that the NABL model is superior to NORAPS for short-range forecasting of elevated trapping layers; however, NABL's ability in surface ducting assessment was found to be limited. It is recommended that the NABL model be upgraded to operational status so that its use in refractivity forecasting and in applications programs which require high resolution boundary layer information can be exploited.

14. Subject Terms.

Atmospheric boundary layer   Numerical weather prediction
NABL   Refractivity forecasting

15. Number of Pages. 32

16. Price Code.

17. Security Classification of Report. UNCLASSIFIED	18. Security Classification of This Page. UNCLASSIFIED	19. Security Classification of Abstract. UNCLASSIFIED	20. Limitation of Abstract. Same as report